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Scaling Relations for Laser Damage Initiation Craters

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Abstract

General physical relations connect the expected size and depth of laser damage induced craters to absorbed laser energy and to the strength of the material. In general, for small absorbers and "instantaneous" energy release, one expects three regions of interest. First is an inner region in which material is subjected to high pressure and temperature, pulverized and ejected. The resultant crater morphology will appear melted. A second region, outside the first, exhibits material removal due to spallation, which occurs when a shock wave is reflected at the free surface. The crater surface in this region will appear fractured. Finally, there is an outermost region where stresses are strong enough to crack material, but not to eject it. These regions are described theoretically and compared to representative observed craters in fused silica.

Keywords: laser damage, scaling, crater formation

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Introduction

Operational UV energy fluences which will be experienced by the NIF final optics are many times smaller than those required for intrinsic optical breakdown. Thus, final optics damage is expected to be initiated by structural and electronic imperfections such as inclusions, cracks, and defects.

Identification of these imperfections and processing modifications to eliminate them would improve the damage resistance of these optics. This approach was successfully used some years ago when Pt inclusions were identified and eliminated from phosphate laser glass [1]. However, it is difficult to apply this approach to presently available high quality fused silica optics. It has been recognized[2] that, at NIF UV fluences, damage can be initiated by strongly absorbing inclusions as small as ten nanometers. In practice, it is very difficult to detect very small absorbing defects somewhere on a large surface at low concentration. Another possible damage initiator is a crack containing material resulting from the polishing process. In such a case, absorption or variation of refractive index is so small that the defects are nearly invisible.

Since UV light absorption by small absorbers results in a large energy density within a small volume, a microexplosion in the material results in an initiation crater. The resulting crater can be easily detected. Studies of these craters can aid determination of the identity of initiators. In the present paper, we theoretically and experimentally analyze damage initiation crater structure in fused silica. We conclude that the observed damage is consistent with the presence of very small near surface absorbers.

The second section describes theoretical models of crater formation. Laser damage crater formation is similar to crater formation due to meteorite impact or to underground explosion, and we have consulted the extensive literature on this subject [3,4]. We obtain crater size estimates as a function of deposited energy and the depth beneath the surface of the energy release. The crater scaling with laser radiation parameters is discussed below. More exact extensive numerical simulations of crater formation are presently being carried out and will be reported in a future publication.

The third section discusses our observed statistics of initiation crater formation. Because modern NIF optics at NIF operating fluences have defects of both small size and low density, as noted above, it is difficult to discover them in experiments with small lasers. To alleviate this issue, we studied crater formation at high laser fluences in non-optimal optics.

The relation between these data and real NIF optics will be discussed in fourth section of the paper. The conclusion summarizes what can be learned about damage initiators from damage initiation crater studies.

Crater model.

We argued in [2] that absorption of laser light by small particles could produce a plasma fireball with size comparable to the laser radiation wavelength λ. Such a fireball, of size, a, will absorb almost all incident energy, so the energy of the fireball can be estimated as $E \sim F\pi\lambda^2$, where F is the laser fluence. The energy density in the fireball is about F/λ. For a fluence of $F=5\ J/cm^2$ and $\lambda \sim 350$ nm, the energy density is $\sim 150\ kJ/cm^3$, approximately 15 times larger than the typical evaporation energy density E_e.

The microexplosion creates a strong shock wave. After this shock wave passes, the resulting crushed material can be described as an incompressible liquid. The strength of the material is taken into account by assuming that the region of crushed material is bounded by the point at which the material velocity v becomes smaller than a critical velocity, c. This velocity, c, can be estimated by $\rho c^2=G$ where G is the characteristic "strength" of the material. For example, the compressive strength of fused silica, G=1 GPa, corresponds to velocity c=670 m/s, much less than the sound speed 5.8 km/sec.

Before presenting specific results, we make some general comments based on scaling. The radius, R, of a crater produced by an explosion with released energy, E, buried a distance h beneath the surface, is determined by E, h, G and ρ. The most general relation between these parameters is of the form

$$R=hf(E/Gh^3) \tag{2.1}$$

where f is a function which needs to be determined from modeling or experimental data. Thus, for craters with the same R/h ratio, the crater size will be proportional to $E^{1/3}$. The scaling law actually observed in experiments with explosives gives an index value between 1/3 and 1/4 [3]. The deviation from $E^{1/3}$ scaling in explosion craters is due to the effect of gravity, which is insignificant for laser damage.

We first describe the crater shape using the incompressible liquid model. The explosion is considered as an instantaneous energy deposition, which initiates material motion. We start with a small absorber placed a distance h beneath the surface. The hydrodynamic potential of the motion induced by the explosion at a point is

$$\phi = A\left(\frac{1}{\sqrt{x^2+y^2+(z-h)^2}} - \frac{1}{\sqrt{x^2+y^2+(z+h)^2}}\right) \tag{2.2}$$

The form of ϕ in Eq.(2.2) is such that the potential and its normal derivative vanish on the free surface. This guarantees the absence of tangential stresses on the surface. The constant A can be determined by calculating the kinetic energy of material motion, proportional to $\frac{1}{2}\int(\nabla\phi)^2 d^3r$ and balancing it with the deposited energy. The integral can be calculated by use of an electrostatic analogy. The potential in Eq.(2.2) is mathematically identical to the electrostatic potential of two charges of opposite sign separated a distance 2h.

It should be noted that the energy of hydrodynamic motion is only part of the total released energy. Some energy is transported by the shock and some is consumed in heating and cracking material. Let α be the fraction of deposited energy going into hydro motion. In explosion experiments, α is typically found to be about 10%. Equating the material kinetic energy to αE, we find

$$A = \sqrt{\frac{\alpha E a}{2\pi\rho}}$$

where E is the released energy, a is the radius of the absorber or zone where the energy was deposited, and ρ is the material density. For laser energy deposition, more than 10% of the released energy can be transferred to material motion. The normal component of material velocity on the surface, u, is

$$u = \frac{2Ah}{\left(r^2 + h^2\right)^{3/2}}; \qquad r^2 = x^2 + y^2$$

Note that the maximal normal velocity, at r=0, is given by

$$u_{\max} = \sqrt{\frac{2\alpha Ea}{\pi\rho h^4}} \tag{2.3}$$

The condition u=c determines the crater radius R:

$$R^2 = \left(\frac{2Ah}{c}\right)^{2/3} - h^2 = h^2\left(\left(\frac{u_{\max}}{c}\right)^{2/3} - 1\right) \tag{2.4}$$

One sees that for an explosion with fixed energy E, there is a maximal burial depth h_d for which a surface crater is formed and a depth h_m for which the resulting crater has maximum size,

$$h_d = \sqrt{\frac{2A}{c}} \quad ; \quad h_m = \frac{h_d}{3^{3/4}} \approx 0.44\, h_d \tag{2.5}$$

Note that Eq.(2.5) implies that the depth for maximum crater size varies only as the 1/4 power of released energy times absorber size. This is different from the scaling in Eq.(2.1) due to the singularity of the hydrodynamic motion, but the difference is small, less than experimental uncertainty. Thus, all craters are expected to be roughly similar over a wide range of energy.

The maximal crater radius is given by

$$R_m = \sqrt{2}h_m \approx 0.6h_d \tag{2.6}$$

At high explosion energy or for shallow absorbers, the crater radius increases as $E^{1/6}$

$$R = \left(h_d^2 h\right)^{1/3} \tag{2.7}$$

To estimate the depth we need to calculate the axial velocity beneath the energy release position. The radial velocity component is zero due to symmetry and the vertical component, u, is given by

$$u(r=0) = \frac{4zhA}{\left(z^2 - h^2\right)^2} \tag{2.8}$$

The condition, u=c, determines the depth d. From (2.8) we have

$$\left(d^2 - h^2\right)^2 = \frac{4Ahd}{c} = 2hdh_d^2$$

For shallow high-energy explosions, the depth of crushed material is

$$d = \left(2hh_d^2\right)^{1/3} = 2^{1/3}R$$

Hence, the crater aspect ratio at high energies (the ratio of depth to the diameter) approaches a universal value of $2^{-2/3} \sim 0.6$. The above estimate indicates the depth of crushed material only. Not all this material will be removed so observed craters must be shallower than this.

In Fig.1 we compare the scaling predicted by Eq.(2.4) with experimental data for strong explosions. The value of the **maximum** depth for which the crater would just open, was used as the only adjustable parameter. We see good correlation with the experimental data.

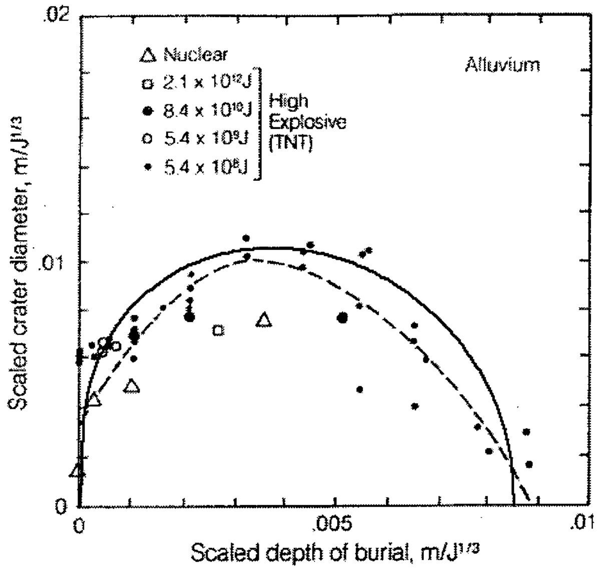

Fig .1: Explosion crater diameter vs. depth of burial in alluvium at the Nevada Test Site [3]. This figure exemplifies $E^{1/3}$ scaling and indicates the importance of the depth of burial for explosions. The dashed line, drawn by the author, is to aid the eye. The solid line is the plot of crater diameter given by Eq. (2.4) below.

We can derive an idea of the size of the various terms above for the laser damage regime by considering some typical values for fused silica. We take the fraction of absorbed energy that appears in mechanical waves, as α=0.1, **a** laser fluence of 10 J/cm^2, and the absorbed energy $F\pi\lambda^2 \sim 10$ nJ. The maximum depth of small absorbers for which surface craters form for 3ω radiation, according to Eq.(2.9), is h_d~1 μm, and the crater diameter ~1.2 μm. We can also apply the experimental explosion data from Fig.1 to the laser damage regime. To use these data, we must take into account that glass is much stronger then alluvium, with G~1GPa, so we rescale the energy according to Eq.(2.1). Taking the experimental value of 2 MPa for the strength of fractured rocks [4], we get HD~2 μm. The agreement between our two estimates is reasonable because of the uncertainty in the yield stress and α. Thus, the incompressible liquid model predicts that typical initiation craters produced by small absorbers should have very small central volumes of crushed material. Fig.(2) shows the crushed material depth-diameter relationship of Eq.(2.4) for the above parameters.

It has been found experimentally that propagation of strong shocks in fused silica glass are followed by a slower moving "failure wave" [5]. After the failure wave has passed, the glass is found to have lost its strength and is crushed. This process occurs more rapidly than excavation by hydrodynamic motion. Thus, for high laser intensities it would be natural to use the strength of crushed rock of 2 MPa in the estimate above. In this case, the maximum crater diameter at 10 J/cm^2 increases to 16 μm.

This suggests a practical formula for estimates of crater size. If we estimate the energy absorbed by the fireball as $E = F\pi\lambda^2$ and use the experimental data from Fig.(1), the crater diameter can be given as

$$d = \left(F\pi\lambda^2 \frac{G_a}{G} \right)^{1/3} \tag{2.9}$$

Here, all lengths are in cm., F is in J/cm^2, G is the effective strength of silica, and G_a is the strength of alluvium.

Initiation Craters in Fused Silica

As mentioned above, the density of defects in NIF optics is so low that in experiments with a small laser beam, it is very difficult to find them. We used high fluence beams to produce surface damage on fused silica with every shot. We assume the underlying initiators at high fluence belong to the same population of defects that cause damage at lower fluence. In Fig.(2), we show multiple damage initiation craters produced by Gaussian beams with maximum fluences of ~ 45 J/cm^2 and 33 J/cm^2. The test beam had a 1/e2 diameter of 0.9 mm and pulse duration of 7.6 ns.

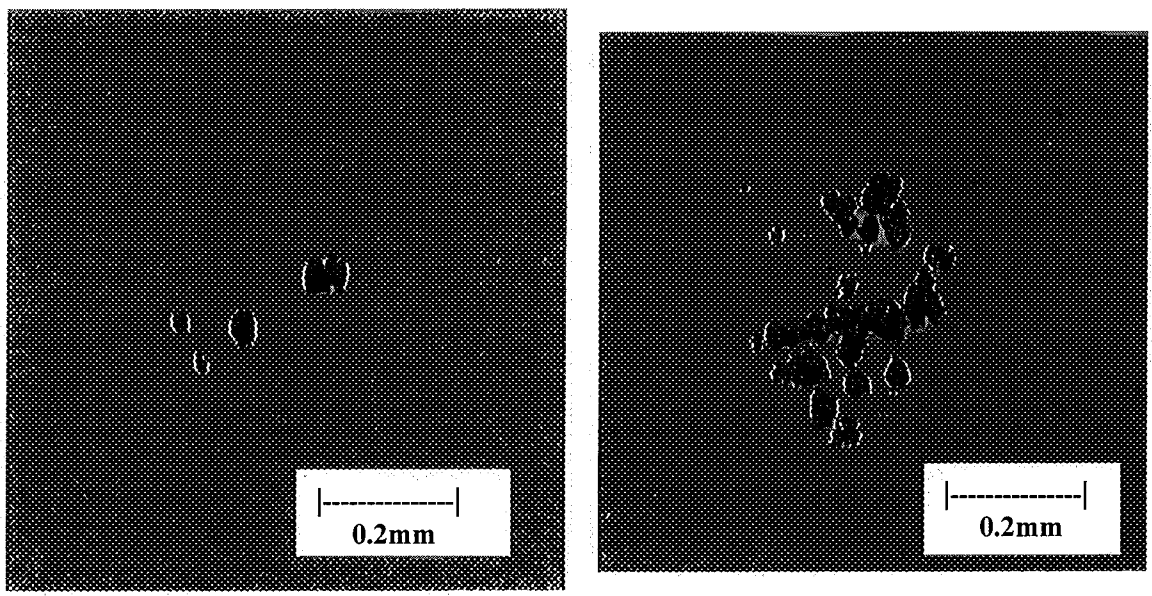

Fig.2 Multiple craters produced at (a) 33 J/cm^2 and (b) at 45 J/cm^2. The microcraters are of similar size in both cases, but their density is different. The beam diameter is about 0.9 mm.

The observed craters vary in size up to about 50 μm in diameter. This size is consistent with Eq. (2.9) if we assume the glass is crushed by the shock and the strength of the crushed material is similar to alluvium. At a fluence of F= 45 J/cm^2, Eq.(2.9) gives d~54 μm, in reasonable agreement.

The density of defects produced by ~ 35 J/cm^2 pulses is substantially smaller than that at the higher fluence, but the crater sizes are almost the same in agreement with the above estimates. It was observed in [6] that the damage density at fluence F increases as a power of fluence,$\sim F^m$, where m is typically large, m~10. The observed density of craters at ~45 J/cm^2 is 5-10 times larger than at ~35 J/cm^2 corresponding to m≈7-9.

Since the damage density is proportional to a high power of laser fluence, the effective area of the beam causing damage is m times smaller than the nominal laser beam area [6]. One can see in Fig.(2) that the damage area is several times smaller than the beam size, which again indicates a large value of m. Of course, this is not the most accurate method to determine the index m , but this result indicates the consistency of the present results and model with that of ref.[6].

A close up view of one of the larger high fluence initiation craters is shown in Fig.(3).

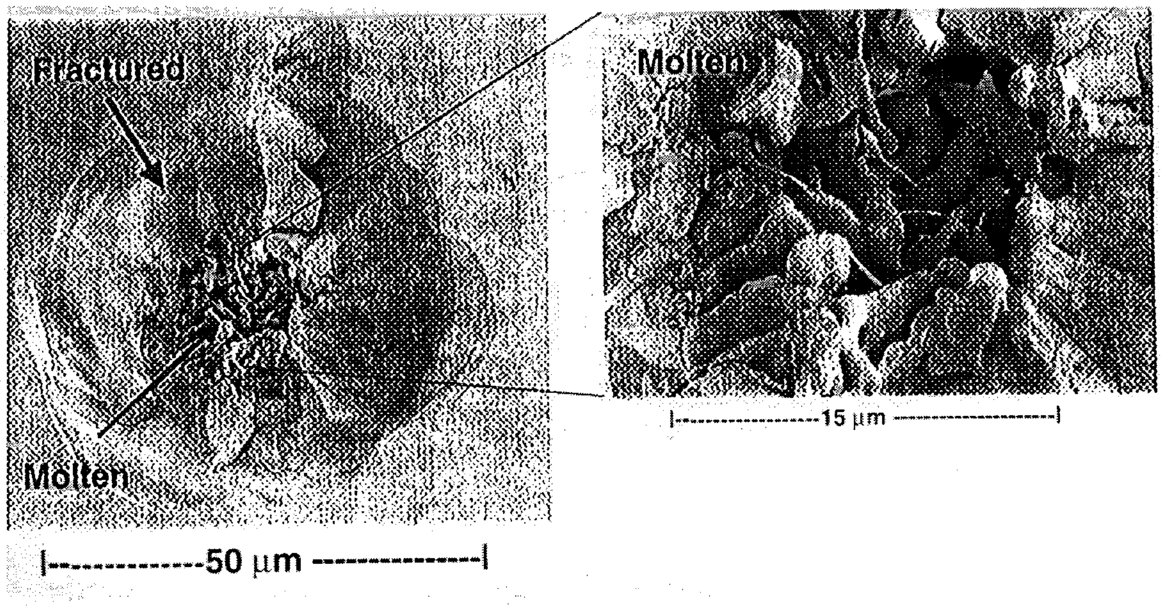

Fig.3: Crater produced by a 45 J/cm^2 shot. Some material is removed by spallation, some by hydrodynamic flow of crushed and melted material.

Smooth structures and filaments in the central region indicate molten material, the result of high pressure and temperature along with material flow. The outer region is fractured most likely the result of spallation accompanying the reflection of the shock wave at the surface.

If identical initiators were distributed homogeneously in the bulk, the distribution of surface craters with respect to diameter would be the same as the distribution of diameters vs. depth shown in Fig.(1). A histogram of crater sizes in one series of experiments is shown in Fig.(4). If the assumptions of uniformity and homogeneity were valid, the observed craters

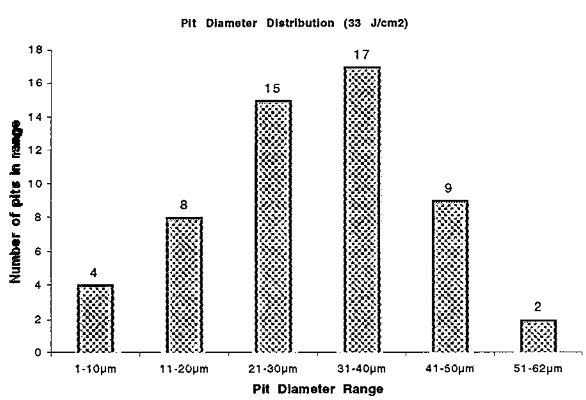

Fig.4 : Typical observed pit diameter distribution

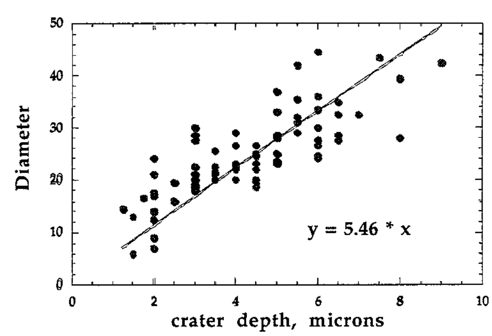

Fig.5: Measured 3ω diameter vs. depth for craters produced by ~45 J/cm^2 shots. The average aspect ratio (diameter to depth) is about 5.5

would exhibit every possible value for the ratio of diameter to depth.

All of our observed initiation craters, however, have large diameter compared to depth (Fig.(5)). This implies the initiators are buried in a subsurface layer at a depth less than h_d. This is consistent with the assumption that initiators are produced during polishing in a modified layer, with thickness less than 1 µm [7].

We measured the ratio of crater diameter to depth. It must be noted that the hydrodynamic model predicts only the boundary of material motion, but cannot say how much material is removed from the crater. Investigators of meteorite impact craters make a distinction between the "transient crater" corresponding to the hydrodynamic model, and the final observable crater resulting from material removal. For small observable craters, where gravity is unimportant, the typical aspect ratio is about 5, i.e., the diameter is 5 times larger than the depth [4]. We observe a similar aspect ratio, (see Fig.(5)). This result is another confirmation of the similarity of meteorite impact and laser damage initiation.

Finally, we note that a different type of crater was observed in studies of so-called "grey haze"[7]. The haze referred to results from many very small craters. "Grey haze" appears at fluences of a few J/cm^2 and is associated with CeO_2 initiators introduced by the polishing slurry[7]. These craters have a smooth morphology with sizes in the range of 1μm. This is consistent with the above estimates if one assumes that the glass is not damaged by the initial shock wave. It is not clear what determines the transition from small smooth to large fractured craters. It is clear that increasing fluence makes the generation of a failure wave more probable. Our experiments show that failure of the glass around the crater does occur at fluences of 30 J/cm^2. It is not evident how much fracture will occur for initiation craters at NIF relevant fluences. The growth upon subsequent laser irradiation of damage craters surrounded by either pristine or failed material must be very different. Clarification of this question is very important for reliable estimates of final optics lifetime.

It is not clear that laser fluence is the only parameter that determines the onset of material failure. Experiments [7] indicate that craters initiated by CeO_2 nanoparticles are small, even at fluences up to ~30 J/cm^2. Probably, in this case the initiators are very close to the optic surface and material ejection can release the pressure before the onset of failure. A more detailed description of fireball growth is required to understand the effect of initiators on damage parameters. Numerical simulations are presently being undertaken to shed light on this issue.

Discussion

We demonstrated above that the observed high fluence damage initiation craters are consistent with the hypothesis of initiation by small absorbers. It is still necessary to study initiation craters produced at NIF relevant fluences to ascertain whether different initiators predominate at high and low fluences. Further studies of these craters can clarify this question.

We found above that initiation craters are expected to have different sizes depending on whether or not the strength of the glass is exceeded by shock waves. Experiments indicate that large fractured craters are produced at high fluences and small craters may be produced at low fluences (grey haze). It would be of considerable interest to observe where the transition from one regime to the other takes place with increasing fluence. This is important because one possible mitigation strategy is to scan an optic to initiate surface damage and then remove the damage site by some kind of etching. It would be easier to mitigate small craters in material that hadn't failed mechanically.

Conclusion

We studied crater formation induced by local absorption of UV radiation. We indicated the similarity of these craters with craters produced by underground explosions and by meteorite impact .The derived scaling laws for crater diameter versus deposited energy, crater morphology and aspect ratio are consistent with our experimental data. We pointed out that mechanical failure behind the induced shock wave may be significant.

This paper describes craters produced by small, sub-wavelength initiators as an aid to identifying such initiators. Initiation craters observed thus far in our experiments are consistent with the hypothesis of small initiators located in a thin subsurface layer. This is evidence for the importance of surface finishing in determining damage vulnerability. It also implies that further surface treatment may be possible to improve optics damage resistance.

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